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14. ABSTRACT The Technology Insertion for Recapitalization of Legacy Systems program consists of two yearlong phases of multiple projects. Phase 1 consists of A) Effect of Corrosion on Physical Properties of Highly Stressed Coated Components, B) Asset Life-cycle Management: Data Needs and Data Gaps Assessment, and C) Subsystem and Component Reliability Synthesis Methodology. Phase 2 consists of D) Suppressing Martensite Formation during Welding of Cast Iron, E) Corrosion Resistant Pin-Joints, and F) Seal Surface Repair using Additive Manufacturing. This report addresses the progress on Phase 1. Under the Corrosion program (A), RIT has identified a remanufacturing process for coated components, as follows: 1) The component coating is to be machined to a minimal thickness without engaging the metal, 2) The coating and corrosion will be removed with a laser, 3) pits will be mechanically removed and the component shot peened, and 4) an Abcite coating will be flame sprayed on the component. The ALCM program (B) has 1) evaluated data provided, 2) gathered questions for analysis, 3) identified gaps in the data, and 4) begun analysis to try to fill the gaps. The Reliability program (C) has 1) built a model framework, 2) evaluated multi-objective optimization methods, and 3) built models of a suspension system for analysis.		

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1. Major Goals: What are the major goals of the project?

The Technology Insertion for Recapitalization of Legacy Systems program consists of 6 individual projects performed in two phases of approximately 1 year per phase. The first phase projects consist of A) Effect of Corrosion on Physical Properties of Highly Stressed Coated Components, B) Asset Life-cycle Management: Data Needs and Data Gaps Assessment, and C) Subsystem and Component Reliability Synthesis Methodology. The Phase 2 projects consist of D) Suppressing Martensite Formation during Welding of Cast Iron, E) Corrosion Resistant Pin-Joints, and F) Seal Surface Repair using Additive Manufacturing.

A) Effect of Corrosion on Physical Properties of Highly Stressed Coated Components

Recapitalization of highly stressed components subject to corrosion requires evaluation of the damage to the coating and the underlying material, and a model for the effect of any damage on the component remaining life. Components with damaged coating or corroded substrate require restoration of both in order to be returned to service.

The goals of this research area are 1) Develop a cost effective, non-destructive methodology to estimate the corrosion damage to a hardened steel component, 2) Develop and evaluate different approaches to remove/repair corrosion damage and develop an approach based on analytical and empirical methods to quantify the impact on fatigue life, and 3) Research and develop methods for restoring damaged organic corrosion control coatings.

B) Asset Life-cycle Management: Data Needs and Data Gaps Assessment

Improved decision-making capability with respect to maintenance, refurbishment, remanufacturing, or upgrade, is needed in order to extend the useful life of high value assets. However the data required to make good life-cycle management decisions with respect to asset reliability is often incomplete or of unknown quality.

The extension of the life-cycle of high value assets has the potential to reduce environmental impacts and also improve cost effectiveness. This includes two important elements: cost effective preservation of asset reliability and availability, and the ability to upgrade the capability of existing assets in order to meet changing market or operational needs. In order to make good life-cycle management decisions at the platform level, or for individual assets, good data is required. This includes information regarding asset and component operational and maintenance histories and information about the cost and availability of spares or technology upgrades for particular components or subsystems.

The goals for this research project are to 1) Document important life-cycle management decisions for ground vehicle applications, 2) Evaluate the availability and quality of data that is required to make these decisions, 3) Identify critical gaps in information content or quality, and 4) Evaluate inference methods for converting raw data to needed life-cycle management decision information.

C) Subsystem and Component Reliability Synthesis Methodology

The operational reliability and total ownership cost of high-value long-life assets change as they age. Required data is not always available to enable traditional reliability modeling approaches, and traditional approaches do not take into account the functional importance of different types of failures.

Decisions about where to invest available funds for the sustainment or upgrade of high value assets are often made without a full understanding of the benefits with respect to reliability, cost, or performance. In order to cost effectively extend the life-cycle of assets without loss in functionality or reliability, it is very important to be able to focus available resources for maintenance or upgrades on the highest impact opportunities.

The goals of this research project are 1) to develop an analysis framework/methodology to assess the reliability, life-cycle cost, and capability benefits of an upgrade or maintenance solution, 2) to provide the ability to allocate reliability requirements associated with an upgrade, based on the best available platform data.

The model framework should support the integration of results from different models that are potentially inter-related, such as detailed physical models of system performance characteristics that are somewhat limited in scope and broader behavioral models such as FMECA models. The framework should also support the integration of empirical models based on field performance data. The overall framework should support the analysis of individual asset behavior, and aggregation to the fleet or platform level. While the framework supports a broader vision, this research will focus on reliability and availability modeling.

D) Suppressing Martensite Formation during Welding of Cast Iron

The high heat input into the cast iron during welding causes excessive martensitic formation which reduces the tensile strength of the weld and fatigue properties of the cast iron adjacent to the weld.

The goals of this project are 1) to evaluate the impact of different levels and means of preheating cast iron prior to a weld repair process, and 2) identify methods of cast iron repair that may be acceptable for various repair procedures. Factors of interest include martensite formation in the cast iron substrate and the tensile strength of the repair.

E) Corrosion Resistant Pin-Joints

Excessive corrosion of pin joints in steel structural members degrades joint performance and can damage the structural members, resulting in high maintenance or replacement cost. The research goals for this project are to 1) Develop a test geometry and accelerated corrosion test for pin joints in steel structural members, 2) Evaluate corrosion counter-measures with respect to rate of corrosion and cost of implementation or retrofit, and 3) Evaluate heat-based processes for joint disassembly that reduce the impact on material properties of the structural member.

F) Seal Surface Repair using Additive Manufacturing

Sealing surfaces in aluminum housings may degrade due to corrosion and wear while the housing still meets other functional requirements. There is a need for a robust repair process for seal surfaces that does not affect the geometric properties or metallurgical properties of surrounding materials.

Laser sintering, thermal spray and cold spray are additive manufacturing methods that may be used to restore components to their original dimensional tolerances. The goals of this research are to 1) evaluate the characteristics of material applied through laser sintering and metal spraying, and 2) identify the technology that is best suited to repairing seal surfaces on aluminum housings with critical dimensional tolerances.

2. Accomplished: What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

A) Effect of Corrosion on Physical Properties of Highly Stressed Coated Components

The initial evaluation of torsion bars identified coating adhesion failures at the ends of the bar. The belief was that if coating delamination could be detected, the bar could be partially stripped and recoated.

1. Develop a Cost-effective, Non-destructive Methodology to Estimate Corrosion Damage

Evaluation of NDE methods to detect delamination and corrosion damage were conducted. Ultrasonic and thermal NDE methods did not work for the torsion bar because the polyurethane coating thickness was not uniform along the length of the torsion bar or around the diameter. Eddy current was also evaluated, but requires that the bar be stripped and that the materials being evaluated are electrically conductive. Since the corrosion products are not conductive this method could not be used.

It was determined that the coating must be removed before measuring corrosion. Pit gauges, profilometers and laser scanners were evaluated. Profilometers and pit gauges require visual identification of a pit prior to measurement, where a laser can find all of the pits without prior knowledge. A scanner can be mounted on the tool holder of the lathe and measure the bar in a single pass.

2. Develop and Evaluate Different Approaches to Remove and Repair Corrosion Damage

a. Coating removal

The manufacturing process of the torsion bar includes a torsional pre-set which yields the base material and causes out-of-roundness in the bar. Since the torsion bar is not round some coating removal processes, such as single point turning were ruled out. While a wire brush could remove the coating without damaging the surface it was time consuming (upwards of an hour) and dirty process. Laser techniques were successful in removing the coating but were also time consuming. Additional methods of coating removal, including sanding, chiseling, slicing, and thermal methods were tested, but proved to be ineffective or too time consuming. The best methods identified utilized a two part process, where the majority of the coating was single point turned and either a laser or wire brush was used for removal of the remaining portion of the coating.

b. Corrosion Removal and Repair

Corrosion removal methods evaluated included wire brush, glass bead blasting, chemical, machining, belt sanding, 3M scotch brite disks and laser. The results showed that methods that easily removed corrosion from the surface (machining, belt, glass bead, and scotch brite) damage the surface. Chemical cleaning was ineffective. Wire brush removed the majority of the corrosion except in deeper pitted areas. Laser cleaning was able to remove the corrosion from the surface without damaging the surface.

c. Develop Approach based on Analytical and Empirical Models to Quantify Impact on Fatigue Life

A robust approach was developed to quantify the impact of corrosion pits and corrosion fatigue on the lives of components. Finite element methods and empirical tests were employed to understand the effect on torsion bar fatigue of intentionally implied residual stresses and stress concentration factors due to corrosion pits. Results showed the aspect ratio, depth/diameter, had the greatest impact on stress. Detailed inspection techniques would need to be applied to quantify this parameter therefore the best option is to remove the pits. Although the bar diameter decreases, the resulting stress is less than that caused by most of the pits observed.

3. Research and Development Methods for Restoring Damaged Organic Corrosion Control Coatings

Table 1 (attachment) shows the application methods evaluated for the restoration process. Unlike the current polyurethane coating, flame spray was ultimately selected because it does not need a primer and it does not have to be dried or cured after application.

Five thermoplastic coatings were selected for evaluation as a corrosion resistant coating – Abcite, PPA 571, G-55, PP10, and G17. These coatings were selected because the physical properties of each coating (Table 2) met the coating specifications in the torsion bar drawings. However, during the testing, the PP10 and G-55 failed to meet the elongation specification. PPA 571 and G17 failed the salt fog corrosion protection test. Only the Abcite coating passed all of the tests in the drawing.

B) Asset Life-cycle Management: Data Needs and Data Gaps Assessment

1. Document important life-cycle management decisions for ground vehicle applications

Utilizing literature searches, first person interviews with ground transportation fleet managers, and discussions with AAV depot maintenance personnel, a series of typical life-cycle decisions were documented and categorized into one of the following categories: Questions that 1) direct overhaul/IROAN strategies, 2) relate to problem detection during overhaul/IROAN, 3) relate to problems with field maintenance procedures or practices, 4) relate to upgrade decisions, and 5) relate to asset utilization and replacement.

Two questions were selected for further evaluation: 1) How should assets be selected for IROAN/overhaul? and 2) How can early engine failures after IROAN be prevented?

2. Evaluate the availability and quality of data that is required to make sound life-cycle management decisions

Data was gathered for field maintenance (2007-2014) and IROAN (2011-2014) for the AAV. Analysis of data identified many data quality issues in the field maintenance data, including inaccurate meter

reading data, labor hours, and serial numbers. IROAN component replacement data is incomplete for some of the years provided.

3. Identify critical gaps in information content or quality

Many of the life-cycle decisions require some understanding of operating context of the asset and failure modes of components, which does not exist in any of the data sets. Maintenance data contains no information about the complaint being rectified. Additionally, even the usage data is of limited use without further analysis and clean-up.

4. Evaluate inference methods for converting raw data to needed life-cycle management decision information

Probabilistic programming models have been used to provide more realistic usage estimates (figure 1). Additionally, efforts are being made to further improve usage estimates based on component replacements (track pads) in the field.

C) Subsystem and Component Reliability Synthesis Methodology

1. Develop an analysis framework/methodology to assess the reliability, life-cycle cost, and capability benefits of an upgrade or maintenance solution

A conceptual design of novel analysis framework that allows for synthesis or decomposition of asset reliability and functionality data by integrating disparate model has been completed. Existing software that leverages development of an analysis framework/methodology for assessment of the reliability, life-cycle cost, and capability benefits of an upgrade or maintenance solution, has been selected, tested, and used to build prototype building blocks of the framework.

Modelica was selected for its use of the functional mockup interface (FMI) whose goal is to support the exchange of simulation models between suppliers and OEMs across various software tools. The Python-based computational environment, with its interface to FMI (JModelica) and the large number of mature libraries was selected as part of the integration framework.

2. Provide the ability to allocate reliability requirements associated with an upgrade, based on the best available platform data

We proposed that a reliability decision support system be based on a pragmatic approach, which considers inputs from disparate sources to fill in the knowledge gaps. Probabilistic graphical models are suitable for problems dealing with complex, non-decomposable models where “ballpark” estimates suffice. This stochastic simulation approach has been identified as a powerful technique for coherent inferencing and selected for the decision-support tool.

3. Training: What opportunities for training and professional development has the project provided?

While studying the effects of corrosion on 300M steel, there has been professional development for researchers at GIS on several different levels. First, as with many organizations the aging population in the US workforce can create a vacuum of knowledge when skilled professionals retired. The many different metallurgical analyses performed during this project afforded younger scientists the ability to learn firsthand from a mentor the procedures, testing methods, and inspection techniques associated with the materials science investigations. An example of this is the technique for examining a fractured surface to locate the initiation point, transition between brittle and ductile failure, and the microstructure or composition associated with changes in the material.

Second, several co-op students were hired during the project which allowed them to understand how to approach technical problems similar to what they will experience through their professional careers. They gained a broad perspective on the project while having individual focus areas to complete during their tenure. The tasks included understanding the latest developments in the field of fracture mechanics associated with mode III crack initiation and propagation. With guidance from senior engineers, students researched fundamentals of fracture mechanics, reviewed related test methods, designed and built a test fixture, and performed experiments to broaden the knowledge base in the scientific community related to this topic.

Third, to complete several aspects of the corrosion research engineers employed the latest versions of non-linear finite element software. In order to accelerate the learning curve for the finite element software engineers undertook group and individual study of processes and implementation methods for execution of the models. The knowledge base and skill level associated with employment of finite element methods has increased through completion of this project. Particular gains were made in understanding the advantages of non-linear software in computing the residual stresses within a component and how they affect the fatigue life of structures.

While completing research for the ALCM and Reliability programs, engineers were introduced to open-source programming language for dynamical simulation (Modelica) and its open-source simulation environments: OpenModelicaEditor, a graphical user interface, and JModelica, an interface to Python-based scientific eco system, which also enables FMI integration of external (non-Modelica) simulators. Engineers trained mechanical engineering co-op students to use these tools for modeling of mechanical systems.

The second self-study was devoted to the theory of multi-objective optimization using evolutionary algorithms (including NSGA-II and SPEA2) and practice using existing libraries compatible with the environment selected for our framework (DEAP, PyGMO). Additional effort was given to visualization of many dimensional Pareto fronts (more than three dimensions). Co-op students were exposed to these ideas and powerful, open-source tools that they can benefit in their future careers.

Finally, a self-study was used to become effective users of probabilistic modeling libraries compatible with the framework environment (PyMC, PyMC3, and STAN), needed to account for uncertainties in decision making in the principled probabilistic way. Engineers and students were also familiarized with the vibrant landscape of probabilistic libraries that also includes BUGS, JAGS, Church, Infer.NET, and others.

4. Dissemination: How were the results disseminated to communities of interest?

During the course of the research program, weekly conference calls were scheduled to share information with the Amphibious Assault Vehicle community. Conference call topics ranged from acceptable processes to be used during refurbishment for the torsion bar to providing useful feedback on the inaccuracies of the data provided for analysis.

An interim review was conducted with the ONR and AAV communities in May. During the review, the three research programs underway were discussed at length. For the corrosion program, in depth discussion of the remanufacturing assessment process occurred. Topics included evaluation and characterization of the component, the techniques for modeling the component to understand impacts of repair procedures, and the evaluation of refurbishment methods and materials.

For the ALCM and Reliability research programs, the AAV community was informed of the significance of some of the data quality issues. Asset usage data was provided in graphical formats that showed the extent to which the data was unreliable. Additionally, the research into modeling frameworks, probabilistic modeling, and the transportation ALCM landscape was presented.

5. Plans: What do you plan to do during the next reporting period to make further progress towards achieving the goals?**A) Effect of Corrosion on Physical Properties of Highly Stressed Coated Components**

The remaining work on the corrosion project consists of 1) performing torsional testing of 300M specimens in a salt water environment to identify the stress intensities associated with torsional loads, 2) finishing a journal publication on the findings of the research, and 3) finalizing the project report. This work is planned to be completed by the end of November.

B) Asset Life-cycle Management: Data Needs and Data Gaps Assessment

The remaining ALCM program work consists of 1) Evaluating additional methods of estimating asset usage (evaluation of regular wear items, such as road wheels or track pads) and combining the results with the Bayesian probability results previously obtained, 2) evaluating the increase in field maintenance costs vs. time, usage and location by subsystem to identify the systems and components that are critical to the need for IROAN, 3) Evaluating of engine repairs both prior to and after IROAN to identify what repairs are contributing to early onset failures and if processes need to be modified during IROAN, 4) evaluating methods of determining the expected influence new data will have on the ALCM models (estimated sensitivity of the model to new factors), 5) formulating a generic methodology to assessing ALCM decisions, and 6) development of the final project report. These tasks are scheduled to be completed by the end of December.

C) Subsystem and Component Reliability Synthesis Methodology

The remaining Reliability program work consists of 1) Refinement of the dynamical models, model parameters and integration with the FEA analysis, 2) Documentation of the case study showing value of the proposed approach for a vehicle life-cycle engineering challenge, 3) Generalization of the

framework, components and processes for other practical problems, and 4) Development of the project report and outreach publications. These tasks are scheduled to be completed by the end of December.

D) Suppressing Martensite Formation during Welding of Cast Iron

Nothing to Report

E) Corrosion Resistant Pin-Joint

Nothing to Report

F) Seal Surface Repair using Additive Manufacturing

Nothing to Report

6. Honors: What honors or awards were received under this project in this reporting period?

Nothing to Report

Technology Transfer

Nothing to Report

Table 1 Coating Application Method Advantages and Disadvantages

Application Method	Advantages	Disadvantages
Brushing	Low capital cost No power requirement No overspray Easy Clean-up	High labor costs Difficult to control coating thickness Drying and curing required after coating
Dipping	Most cost effective coating process May be automated or manual High production capacities No overspray Able to coat inner and outer diameters	High capital costs Geometry and size of torsion bars no ideal for this application method - Uses large volumes of coating Coating tends to build up at bottom of article Drying and curing required – generation of VOC possible
Air and Airless Spray	Fast Application method Control of Film thickness Allows for use of fast drying coatings	Need an experienced operator Requires a special spray booth to limit overspray and protect operator Requires primer or surface treatment for improved adherence Drying and curing required –generation of VOC possible Equipment requires extensive cleaning after use Coating can build up on cap or in orifice during coating
Flame Spray	Fast Application method High transfer efficiency Able to control of Film thickness No drying or curing required No surface pretreatment required for adherence No or only small amount of overspray No spray booth required Quick clean-up	Limited amount of coating compositions available Article must be preheated to 150 to 200F Small open flame if use propane
Electrostatic	Dries Quickly High transfer efficiency Durable coatings	Very high start-up coats High VOC content –required spay booth to control build-up of toxic fumes Requires curing after application

Table 2 Physical Properties of Thermoplastic Candidate Coatings

	Abcite	Polyoefins PPA 571	Polypropylene G-55, PP10	Polyethylene G-17
Impact Resistance	Excellent	Excellent	Excellent	Excellent
Melt Point (F)	203	310	225	221
Hardness (Shore D)	50	63	53	55
Elongation at Break	580%	500%	900%	498%
Tensile Strength	16 MPa	18 MPa	14 MPa	24 MPa
Salt Spray Resistance	Excellent	No data	Excellent	Excellent
UV Resistance	Excellent	Good	Excellent	Excellent

Figure 1 Probability model results showing the probability distribution of likely meter readings for each field maintenance event

